Working Group Summary: Chiral Dynamics in Few-Nucleon Systems

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We summarize the findings of our Working Group, which discussed progress in the understanding of Chiral Dynamics in the $A = 2$, 3, and 4 systems over the last three years. We also identify key unresolved theoretical and experimental questions in this field.

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1. Introduction

This year is the tenth anniversary of the first quantitative treatment of the nuclear force based on chiral perturbation theory (χPT): the seminal paper of Ordóñez *et al.*[1] This paper employed Weinberg's proposal to expand the NN potential up to a given chiral order:

$$V = V^{(0)} + V^{(2)} + V^{(3)} + V^{(4)} + \ldots, \tag{1}$$

and then use the resulting potential in the Schrödinger equation and obtain the NN wave function.[2] However, in that same year Kaplan, Savage, and Wise raised serious questions about the consistency of such an approach.[3]

The paper of Ordóñez *et al.* analyzed NN scattering data using an NN potential which included all mechanisms up to next-to-next-to-leading order ($\mathrm{N^2LO}$). This has now been extended to one higher order,[4,5] and the

result is an energy-independent potential that describes NN data with an accuracy comparable to that of the "high-quality" NN potentials. However, questions remain about the consistency of the power counting used to derive this N^{3}LO potential.[6–8] These questions were discussed in a special "panel" format within our Working Group. The conclusions of this panel are summarized in Section 2.

At the same time lattice simulations have made significant strides in connecting these chiral potentials to QCD itself. The work of the NPLQCD collaboration is also discussed in Sec. 2, and it shows that NN scattering lengths are natural at quark masses corresponding to $m_\pi \geq 350$ MeV.[10] Chiral extrapolation from the physical point to these higher values of m_π shows that the numbers obtained in the simulations are consistent with the experimentally measured "unnaturally large" ($|a| \gg 1/m_\pi$) values:[9] $a^{^3S_1} = 5.4112(15)$ fm and $a^{^1S_0} = -23.7148(33)$ fm.

The existence of these large scattering lengths leads to "universal" features in the dynamics of few-nucleon systems. These are a consequence solely of the scale hierarchy $|a|m_\pi \gg 1$, and are independent of details of the nuclear force. There has been much recent progress on calculations in the universal effective theory without explicit pions that describes this physics. This provides the opportunity to compare precise, low-energy ($E < \frac{m_\pi^2}{M}$) scattering experiments in the three- and four-nucleon systems with a theory where calculations can be carried out with a comparable degree of control. Progress in this direction in both theory and experiment is discussed in Sec. 3.

At higher energies three-nucleon scattering experiments must be analyzed using theories in which the pion is an explicit degree of freedom. Recent experiments have produced a wealth of data, including single- and double-polarization observables, over a range of energies. Ideally one would analyze these data using nuclear forces derived from χPT. The great benefit of such an approach is the ability to derive three-nucleon (and, if desired, four- and five- and six-...) nucleon forces within the same framework, and to the same order in the chiral expansion, as is used for the NN force. This is discussed in Sec. 4.

As with n-body forces, the operators that describe the interaction of external probes (electrons, photons, pions, ...) with the nucleus can also be expanded up to a chiral order that is consistent with the order used to analyze the NN potential. This "chiral effective theory" (χET) approach has now been applied to many reactions in the NN system, and calculations of reactions on the tri-nucleons are just beginning. These methods

are particularly valuable in facilitating the extraction of neutron properties from experiments on multi-nucleon systems. Neutron polarizabilities are observables that have recently received particular attention in this regard. Progress in these areas is summarized in Sec. 5. In addition to the topics discussed explicitly there, related talks by F. Myhrer on $pp \to pp\pi^0$ and S. Nakamura on the renormalization-group behavior of weak current operators were also presented to the Working Group.

Finally, chiral perturbation theory is being used to analyze symmetry breaking in the NN system. New work on how parity-violating operators appear in the NN system provides a framework for the analysis of a new generation of experiments that probe hadronic parity violation. Isospin violation can also be included in the NN potential using χPT techniques, and this allows a careful examination of how isospin-violation effects appear in various reactions. These issues are discussed in Sec. 6.

2. The *NN* system: still fighting after all these years

2.1. *Connection to lattice QCD*

One of the major developments in the NN system since CD2003 is the first NN lattice calculation in full QCD.[10] The NPLQCD collaboration computed QCD correlation functions by using Monte Carlo techniques to evaluate the QCD path integral on a discrete Euclidean space-time lattice. This starts directly from QCD, thereby allowing truly "*ab initio*" calculations of nuclear physics observables. However, the computational effort required for these calculations increases sharply (i) with the number of valence quarks involved and (ii) as the light quark masses are lowered to approach physical values.

S. Beane reported on these results of the NPLQCD collaboration. Their hybrid calculations used configurations generated by the MILC collaboration including staggered sea quarks and they evaluated the NN correlator in this background using domain-wall valence quark propagators. Applying the Lüscher method, the spin-singlet and spin-triplet S-wave scattering lengths were extracted at three different pion masses between 350 and 590 MeV. At the lowest pion mass the values $a^{^3S_1} = (0.63 \pm 0.74 \pm 0.2)$ fm and $a^{^1S_0} = (0.63 \pm 0.50 \pm 0.2)$ fm were found. At this pion mass the errors from a chiral extrapolation to the physical m_π are still large, but chiral extrapolation from $m_\pi = 139$ MeV shows that the result is consistent with the experimental values, within (sizeable) error bars.

Thanks to continuing advances in computer power much progress in this

direction can be expected over the next three years. Lattice computations of NNN correlators are a high priority since they will provide access to three-nucleon forces directly from QCD, but algorithmic and theoretical advances will be required in order for such calculations to become a reality.

2.2. *Panel on power counting for short-distance operators*

Fifteen years after Weinberg's seminal papers on a chiral effective theory description of nuclear physics, questions about this technique remain. The power counting (1) is quite successful phenomenologically, but various recent papers have questioned its validity.[6–8] As part of the working group, we had a panel discussion with U. van Kolck, U.-G. Meißner, and M. Pavon in order to try and shed some light on this important issue.

The key problem is how to renormalize the Schrödinger equation with (attractive) singular potentials. When the equation is solved there are two acceptable wave-function solutions at short distances. The "correct" linear combination must be fixed by physics input. This can be implemented by adding a contact potential in such channels. How many contact terms are required when the NN potential is computed to a given order in the chiral expansion? So far this question has only been intensively studied for the leading-order (LO) potential. That the inclusion of one such contact term renormalizes the ${}^3\mathrm{S}_1$-${}^3\mathrm{D}_1$ channel at LO was established in Refs. 11–13. This vindicated Weinberg's counting in that channel. However, Ref. 12 confirmed that an additional m_π-dependent contact term must be considered in the ${}^1\mathrm{S}_0$ channel for renormalization there.[3] The issue of how many contact terms to include in V in other channels, where Weinberg's counting does not indicate the presence of such a contribution at LO, is still a controversial one. Two main points of view on this issue were presented in the panel.

U. van Kolck argued that the necessity for the inclusion of contact terms beyond those present in Weinberg's counting is dictated by strict renormalization-group invariance of observables. Renormalization is achieved when the effects of the cutoff Λ are of the size of higher-order terms in the χET. But when Λ is varied over a wide range, unphysical bound states appear in the NN spectrum. The only way to then guarantee renormalization-group invariance of NN observables is to introduce additional contact terms which renormalize V. Typically the necessity for these extra operators to be included arises when Λ is larger than the breakdown scale of the theory, which is usually taken to be of order m_ρ. For example, in Ref. 7 renormalization of the ${}^3\mathrm{P}_0$ phase shift for energies up to 100 MeV is achieved for $\Lambda \geq 8\ \mathrm{fm}^{-1}$, but only after a contact term that operates

in this wave is included in the LO calculation. M. Pavon's results support this point of view, although the formulation employed in his work involved imposing boundary conditions on the radial wave function at a very short distance. He also used the requirement that wave functions corresponding to different NN energies should be orthogonal to derive restrictions on the maximum number of contact terms that can be included in a given channel.

The contrasting view was advocated by U.-G. Meißner: that calculations should only be carried out with a finite cutoff Λ which is of the order of the expected breakdown scale of the χET, m_ρ. Strict renormalization-group invariance is not required, but the cutoff should be varied around m_ρ in order to get a lower bound on the size of omitted short-distance physics. There is no point in considering $\Lambda \gg m_\rho$, since the error in the calculation is not expected to decrease in this regime.[14] In this case, the coefficients of short-distance operators scale as predicted by naive dimensional analysis with respect to Λ, and Weinberg's counting holds. In Ref. 15 Epelbaum and Meißner examined the behavior of NN phase shifts and compared to the results of Nogga *et al.*[7] They found that a result for the $^3\mathrm{P}_J$ waves that deviates from the asymptotic result of Ref. 7 by less than the theoretical uncertainty of a LO calculation could be achieved for $\Lambda \sim 600$ MeV.

During the discussion no consensus was achieved between the panelists. Fundamental disagreement remained about whether it was necessary to consider cutoffs $\Lambda \gg m_\rho$. Meißner argued that Ref. 15 showed that for all practical purposes the range $\Lambda \lesssim m_\rho$ contained all useful information. A. Nogga pointed out that it would not have been possible to reach this conclusion—independent of data—in Ref. 15 if the cutoff-independent phase shifts of the analysis of Ref. 7 had not already existed. Following this argument, for each new order in V, an analysis which demands strict renormalization-group invariance may be necessary before we can identify regions in Λ-space where Weinberg's counting can be used in practice.

Meißner in particular, felt that no conclusions could be drawn about power counting for short-distance operators until their role in renormalization had been examined with V calculated to orders beyond leading. Some of the contact terms promoted to LO in the study of Ref. 7 appear in the NLO potential, and (almost) all of them are present by N^{3}LO. Therefore in N^{3}LO calculations employing Weinberg's counting may be consistent with the requirement of Λ-independence over a broad range. Such a resolution is possible because, for high enough J, phase shifts can be calculated in perturbation theory throughout the entire energy range for which χPT is valid. However, it should also be noted that as higher orders are consid-

ered the long-distance part of V becomes even more singularly attractive in some of the P- and D-waves discussed by the panel. Whether this leads to further difficulties for Weinberg's power counting remains to be seen. Indeed, issues associated with V at NLO and beyond can only be resolved by calculation, and the majority of Working Group participants felt that studies which examine such issues are very important.

2.3. *πNN coupling constant controversy resolved*

In the NN system, many measurements have been performed in the last 30 years. In 1993 the Nijmegen group performed a partial-wave analysis (PWA) of these data, and thereby obtained a statistically consistent database of over 4000 np and pp data.[16] In doing this they found a (charged) πNN pseudoscalar coupling of $\frac{g^2}{4\pi} = 13.54 \pm 0.05$. This disagreed with a dedicated measurement of backward-angle np scattering at Uppsala, which yielded a result consistent with the "old" higher value $\frac{g^2}{4\pi} \approx 14.4$.[17]

S. Vigdor gave an overview of a recent experiment aimed at resolving this discrepancy.[18] In this double-scattering experiment, the flux of the neutron beam was accurately determined by counting the outgoing protons in the reaction ^{2}H$(p,n)2p$ that produced the beam. The results of this absolute np differential cross section measurement at backward angles and a lab energy of 194 MeV are consistent with the predictions of the Nijmegen PWA. The NN database therefore now provides an accurate and unambiguous determination of the $\mathcal{L}^{(3)}_{\pi N}$ LEC b_{19}, which is associated with the Goldberger-Treiman discrepancy.[19]

3. $p \ll m_\pi$: low-energy dynamics which isn't chiral

3.1. *N^{2}LO and beyond in the three-nucleon system*

One of the central goals of nuclear physics is to establish a connection to QCD and its spontaneously broken chiral symmetry. There are some properties of nuclear systems that are due to chiral dynamics. Other properties, however, are simply a consequence of the (apparently accidentally) large scattering lengths. Such properties are "universal": they occur in a wide variety of systems from atomic to nuclear to particle physics,[20] and can be studied in an effective field theory (EFT) with contact interactions only. In nuclear physics, this is a "pionless" theory, which can be applied to processes with typical momenta $p \ll m_\pi$ and no external pions. It allows for precise calculations of very low-energy processes and exotic systems with weak binding such as halo nuclei.

L. Platter gave an overview of the pionless theory and showed various applications from atomic and nuclear physics. He presented results from his recent calculations of nd scattering and the triton that included all effects up to second order in p/m_π (i.e. N^{2}LO in this EFT) using a subtractive renormalization scheme.[21,22] (For an overview of previous higher-order calculations in the pionless theory see Ref. 20.) Platter's results imply that only the two-body S-wave scattering lengths and effective ranges plus one datum from the three-body system (usually taken to be $a_{nd}^{(1/2)}$ or the triton binding energy) are needed to predict low-energy three-nucleon observables with an accuracy $\sim 3\%$. As a consequence, universal correlations such as the Phillips and Tjon lines, as well as an analogous correlation involving the triton binding energy and charge radius,[23] persist up to N^{2}LO.

For precise higher-order calculations, it is important to know at which order new three-body force terms appear.[24] A general classification of three-body forces in this theory was presented by H. Grießhammer. He also illustrated the practical usefulness of the pionless theory by showing precise predictions for a recent deuteron electrodisintegration experiment at S-DALINAC,[25] and threshold neutron-deuteron radiative capture.[26]

3.2. *Experimental input and output*

Low-energy neutron-deuteron (nd) scattering is characterized by two scattering lengths: one in the quartet ($J = 3/2$) and one in the doublet ($J = 1/2$) channel. A novel method for measuring the incoherent combination of these using polarized scattering was outlined by O. Zimmer. His experiment obtains the incoherent nd scattering length from the pseudomagnetic precession of neutrons in a mixture of polarized deuterons and protons. Combining with the well-known coherent scattering length yields an anticipated accuracy for $a_{nd}^{(1/2)}$ that is a factor of 10 better than the present value $a_{nd}^{(1/2)} = 0.65 \pm 0.04$ fm.[27] Since $a_{nd}^{(1/2)}$ is an input to pionless EFT calculations in the three- and four-nucleon sectors this experiment should also lead to more accurate predictions from that theory.

With the ingredients of the calculations for the NNN system under control at low energies, theoretical attention is turning towards $4N$ systems. The four-body system provides a fertile laboratory for few-body physics since many features such as resonances and multiple thresholds are present there, but are absent for $A < 4$. $4N$ systems are also the simplest ones where amplitudes of isospin T=3/2 can be studied in the laboratory. T. Clegg presented a talk on recent measurements and plans for new measurements using the recently developed polarized ^{3}He target at TUNL in combination

with polarized proton and neutron beams. In addition to analyzing powers, spin-correlation coefficients have been measured.

3.3. *The future*

The future of the pionless theory lies in the extension to larger systems and in more precise higher-order calculations. The new precise $3N$ and $4N$ data from TUNL provide a challenge for the pionless theory program. The best known example is the A_y puzzle which is a long-standing problem in few-nucleon physics. There are dramatic effects in the vector analyzing powers at low energies where the pionless theory is applicable. As emphasized by T. Clegg, these effects become more severe for higher target masses which underscores the necessity for a better understanding of the four-body system. Currently, only a leading-order calculation is available and the general power counting of four-body forces is not understood.[28] As a consequence, more theoretical work is required. Many more interesting calculations and experimental results pertinent to $4N$ systems can be expected before the next Chiral Dynamics workshop.

The extension to systems with $A > 4$ appears to be an opportunity for lattice implementations of the pionless theory. As discussed by D. Lee, the renormalization-group behavior of the three-body force was already verified and lattice techniques have successfully been applied to dilute neutron matter.[29,30] These techniques can also be extended to the theory with pions, and may provide novel ways to compute nuclear bound states from χPT.

4. Going higher in the NNN system

In the past fifteen years, experimental and theoretical developments in the NNN sector have taken place hand-in-hand. The numerical solution of Faddeev equations describing three-body systems has become routine, while high-precision experimental data have become available thanks to a new generation of experimental facilities. These include Bonn and Cologne in Germany, Kyushu in Japan, and TUNL in the US for low energies, and KVI in the Netherlands, RIKEN and RCNP in Japan, and IUCF in the US for intermediate energies. In this section, a summary of the measurements performed for the intermediate energies will be presented.

J. Messchendorp gave an overview of the experiments performed at KVI in the past 10 years on the elastic and break-up channels in proton-deuteron scattering. K. Sekiguchi presented data from Japan on the elastic and break-up channels in nucleon-deuteron scattering.[31] There is a persistent problem

of disagreement between the elastic *pd* cross sections measured at KVI and RIKEN at 135 MeV, but the bulk of data (including analyzing powers) taken at both laboratories show unambiguously the need for an additional ingredient in the theory beyond standard NN potentials. In some cases the addition of phenomenological NNN forces brings the results into very good agreement with the data but elsewhere, particularly at higher energies, these three-nucleon forces do not resolve the discrepancies between the data and the calculations. Unfortunately, the χET calculations at N^3LO required to accurately predict NNN system observables for energies larger than 100 MeV/nucleon have not yet been carried out, and only calculations with phenomenological potentials are available for this energy range.

In order to understand the spin structure of three-body forces, double-scattering experiments with polarized deuteron beams have been performed at both KVI and RIKEN. Spin-transfer coefficients from the deuteron to the proton have been obtained with rather high precision for a large part of the phase space.[32] These measurements have been performed at lower energies, allowing a comparison with the N^2LO predictions from χET computed by Witala and collaborators.[33] Within the relatively large error bands of the calculations there is good agreement with the data, but some discrepancies remain. The need to go to higher orders in χET is obvious.

The progress being made in this direction was described in the talk of E. Epelbaum. As explained above, the N^3LO NN force already exists, and gives results in quite good agreement with NN data. Work on deriving the (parameter-free) N^3LO NNN force is ongoing. Results that have been obtained so far for certain classes of diagrams were presented. Completing the calculation of the full set of N^3LO NNN force diagrams and comparing N^3LO predictions with experimental data will be a key test of χET's usefulness in three-nucleon systems, and we anticipate results by CD2009. Epelbaum also outlined his derivation of a parameter-free $NNNN$ force, which enters the nuclear potential at N^3LO.[36] This is the first microscopic computation of a $NNNN$ force, and estimates of its impact on α-particle binding suggest a 200–400 keV effect.[37]

Returning to experimental results, both Sekiguchi and Messchendorp presented *pd* break-up data, which showed the rich phase space offered by this channel. Not surprisingly, the data supports the inclusion of NNN forces. For the kinematics where the relative energy of the two outgoing protons in the break-up reaction is small one expects sensitivity to Coulomb effects. These effects have now been explicitly included in the calculations of the Hanover-Lisbon group[34] and have been examined and shown to exist

by the Cracow-KVI measurements.[35] Proton-deuteron break-up data can thus be analyzed in a theoretical framework which makes it clear which effects are due to the Coulomb interaction. Therefore, we are no longer restricted to examining only *nd* breakup data. This provides a much richer NNN database within which we can look for the effects of chiral dynamics.

Messchendorp noted that the coupled-channels calculations of the Hanover-Lisbon group, which treat the $\Delta(1232)$ as a dynamical degree of freedom, do reasonably well when compared to the measured data in all of the channels discussed above. This might point to the fact that calculations of these observables in χET should include an explicit $\Delta(1232)$—especially if they wish to address data at higher energies. This could improve the convergence of χET calculations, which at present show a sizeable shift between NLO and N^{2}LO (c.f. Ref. 1). This shift signals the impact of two-pion-exchange in both the NN and NNN forces. As such it is a place where χET gives concrete predictions for the impact of two-pion-exchange physics on *nd* and *pd* elastic and breakup data. More calculations that highlight the impact of chiral physics on these data are needed.

However, further opportunities for measurements of this physics appear dangerously limited. The database in the NNN system remains much poorer than that in the NN system, but many laboratories studying this physics have shut down in the past few years and more will cease operations in the near future.

5. Soft Photons and Light Nuclei

Electromagnetic reactions on light nuclei can also be calculated within χET. After using the chiral potential of Eq. (1) to generate a wave function $|\psi\rangle$ for the nucleus—and, in breakup reactions, a consistent wave function for the final scattering state $|\psi_f\rangle$—one derives the current operator, J_μ for that system, again up to a given chiral order. The matrix element $\mathcal{M} \equiv \langle\psi_f|J_\mu|\psi\rangle$ can then be computed.

5.1. *Electron-deuteron scattering*

Work on current operators for the NN system has been going on for more than 10 years now. Park, Min, Rho, and later collaborators have computed deuteron photo- and electrodisintegration as well as weak reactions using a hybrid approach where J_μ is sandwiched between wave functions obtained from the AV18 potential (see, e.g. Refs. 38,39). More recently, computations of elastic electron-deuteron scattering using both V and J_μ computed up

to NLO[40] and N^2LO[41,42] in the chiral expansion have been carried out. At N^2LO these calculations seem to agree—within the combined theoretical and experimental error bars—with the preliminary BLAST data presented in the talk of R. Fatemi.

5.2. *Compton scattering in $A = 2$ and $A = 3$*

Compton scattering from nucleons probes chiral dynamics in novel ways that explore the interplay between the long-range pion cloud and short-range operators in chiral perturbation theory.[43] The spin-independent polarizabilities for the proton are now quite well established, but the equivalent quantities for the neutron are not as well constrained by existing experimental data. Better knowledge of α_n and β_n would provide more information on how chiral dynamics in Compton scattering expresses itself differently among the two members of the nucleon iso-doublet.

H. Grießhammer reported on recent advances in calculations of elastic γd scattering. He and his collaborators have developed a new power counting for γd, designed for photon energies $\omega \sim \frac{m_\pi^2}{M}$. In this regime, the usual χPT counting cannot be applied to the $\gamma NN \to \gamma NN$ operator, and resummation of certain classes of diagrams is mandatory. When this resummation is complete the calculation reproduces the Thomson limit for the zero-energy γd cross section.[44] This also reduces the theoretical uncertainty in the calculation due to different assumptions about short-distance physics. Thanks to these advances, as well as the inclusion of $\Delta(1232)$ effects that are important at $\omega \sim 100$ MeV and backward angles, α_n can now be extracted from the extant γd data with a precision of about 15%.[44]

This is particularly exciting in light of the new data anticipated from MAX-Lab. As described by K. Fissum in his talk, an experiment that is scheduled to begin there next summer will approximately quadruple the world data on γd scattering. Taken in concert with theoretical advances this should facilitate an extraction of spin-independent neutron polarizabilities at a precision comparable to that at which α_p and β_p are known.

D. Choudhury reported on the first calculation of Compton scattering from the Helium-3 nucleus. Her χET calculation shows that there is significant sensitivity to neutron spin polarizabilities in certain γ^3He double-polarization observables. There are plans to measure these at the HIγS facility. Within Choudhury's NLO calculation, a polarized ^{3}He nucleus behaves, to a very good approximation, as a polarized neutron. Neutron spin polarizabilities can also be probed in $\vec{\gamma}\vec{\mathrm{d}}$ measurements at HIγS,[45] which provides an important cross-check on our ability to calculate "nuclear" ef-

fects in Compton scattering.

Further progress in χET calculations will reduce the theoretical uncertainties that arise when neutron polarizabilities are extracted from γd or γ^3He data. Meanwhile, accurate polarized and unpolarized data on these reactions are anticipated from MAX-Lab and HIγS. With lattice QCD beginning to make predictions[46,47] (albeit quenched ones) for baryon polarizabilities there is an exciting opportunity for χET to connect experimental data from few-nucleon systems to the results of lattice simulations.

5.3. *Photodisintegration*

A number of talks discussed photodisintegration of light nuclei as a probe of nuclear forces. W. Leidemann argued that this a particularly attractive possibility, because the Lorentz Integral Transform (LIT) is a technique by which bound-state methods can be used to take a given NN and NNN force and obtain predictions for the photodisintegration cross section.

The resultant predictions (with phenomenological force models)[48] for the photodisintegration of ^{4}He are in agreement with the data from Lund presented in the talk of K. Fissum.[49] They do not, however, agree with a recent experiment at RCNP in Japan which used a novel technique.[50] P. Debevec described an experiment that could be done at HIγS which, with careful control of systematics, could pin down this cross section with very small error bars. Fissum also anticipates a future experiment at MAX-Lab could significantly reduce the error bars obtained in Ref. 49.

All of these experiments bear on the height of the first peak in the γ^4He cross section. This quantity contains important information on nuclear dynamics, and as such can be used to constrain χET (and perhaps even pionless) descriptions of nuclear forces. A computation of ^{4}He photodisintegration within χET is therefore a high priority, as is a definitive experiment to resolve the discrepancies in the present ^{4}He photoabsorption data. Meanwhile, more detailed information on nuclear forces in general, and the χET NNN force in particular, is expected from measurements of three-body breakup (with neutron detection) of polarized ^{3}He by linearly-polarized photons. These experiments will take place at HIγS, and were described by X. Zong.

5.4. *The Future*

Few-body methods such as the LIT, combined with χET expansions for the nuclear potential and electromagnetic current operators, provide opportu-

nities to confront χET predictions with existing data on electromagnetic reactions on light nuclei. But only a few groups world-wide are performing such calculations, so this opportunity may not be fully exploited. And as photon and electron machines shut down or increase their energy, the possibility to use real and virtual photons to probe chiral dynamics in light nuclei may disappear. Over the next few years the role of experimental facilities such as MAX-Lab and HIγS will be vital.

6. Frontiers in symmetry breaking

6.1. *Parity violation*

A discussion of hadronic parity violation experiments was presented by S. Page. Various probes in few-body systems were discussed. An experiment which is taking data presently is polarized neutron radiative capture on protons at LANSCE. By measuring the very small ($< 10^{-7}$) up-down γ-ray asymmetry, one can constrain the low-energy constants that represent parity-violation in the χET,[51] e.g. the parity-violating πNN coupling constant sometimes called $h_{\pi NN}$.

6.2. *Isospin violation*

The light-quark mass difference $m_u - m_d$ is only a small fraction of the total mass of the nucleon. But the large NN scattering lengths magnify this isospin-breaking to the point where it is a $\sim 10\%$ effect in $a_{nn} - a_{pp}$.

Theoretical extractions from pp data yield a strong proton-proton scattering length of $a_{pp} = -17.3 \pm 0.4$ fm.[52] However, up until now, the neutron-neutron scattering length, a_{nn}, has only been extracted from few-body data. Different experiments on nd breakup lead to numbers that disagree, as described in the talk of C. Howell. Over the next three years we can anticipate new data on a_{nn} from at least two sources: a (hopefully) definitive nd breakup experiment underway at TUNL, and a re-analysis of LAMPF $\pi^- d \to nn\gamma$ data, discussed in the talk of A. Gårdestig. In addition, the contribution of V. Lensky pointed out that $\gamma d \to nn\pi^+$ could provide a complementary a_{nn} extraction. Once HIγS attains energies above pion threshold such an experiment could perhaps be done there.

The NPLQCD collaboration has already examined the impact of $m_u - m_d$ on the neutron-proton mass difference.[53] If this calculation could be extended to NN correlators, and the impact of $m_u - m_d$ on $a_{nn} - a_{pp}$ predicted, it would allow us to confront lattice results with high-precision extractions of the scattering-length difference from few-nucleon systems.

7. Conclusion

All of this suggests an exciting future for Chiral Dynamics in these systems. An era of calculations of few-nucleon bound states and reactions that truly start from QCD is just beginning. The presentations at CD2006 allow us to foresee a future where lattice simulations provide constraints on the low-energy constants that appear in the χET, and few-body methods allow us to completely solve—even for systems with $A = 4$ and beyond—that effective theory up to a fixed order in the chiral expansion. The resultant computations, which involve a mix of lattice, effective theory, and traditional few-body techniques, can then be compared (including their theoretical uncertainties!) with the wealth of experimental data in the $A = 2, 3$ and 4 sectors. We look forward to significant progress in the formation of this linkage between the chiral dynamics of QCD and the behavior of few-nucleon systems by the time of CD2009.

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